Challenges in Aircraft Engine Gas Path Health Management

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Challenges in Aircraft Engine Gas Path Health Management
Outline

- Aircraft Engine Gas Path Health Management Background
  - Goals and Benefits
  - Approaches

- Future Challenges
  - Data quantity, data access, and data sharing
  - New sensor suites
  - Benchmarking and verification & validation methods
  - Models and model-based controls & diagnostics
  - Engine fault testing
  - Information fusion
  - Practical design considerations

- Summary

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Challenges in Aircraft Engine Gas Path Health Management
Background

Gas Path Health Management is a Critical Element of an Aircraft Engine Health Management System

Closely Coupled

Vibration

Lubrication System

Component Life Usage

Gas Path

Electronic Engine Control

Engine Health Management System

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Aircraft Engine Gas Path Diagnostics Architecture

Engine

Sensed Measurements
- Pressures, temperatures, rotor speeds, etc.

- **Enabled by digital engine controls and data acquisition systems**

- **Both on-board and off-board functionality**

On-Board Diagnostics

FADEC

On-Board

Data - Transmission

Off-Board (Ground-Based)

Fleet-wide Trend & Condition Monitoring

Ground Station

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Aircraft Engine Gas Path Health Management

Goal: **Through the interpretation of measured aircraft engine gas path parameters…..**

- **Accurately assess engine component performance deterioration over an engine's lifetime of use**

    - and -

- **Accurately detect and isolate any engine system and/or instrumentation malfunctions that occur**

Benefits: **Inherently tied to …**

- **Safety**

    - and -

- **Affordability**

Reduced in-flight malfunctions

Reduced maintenance-related delays and cancellations

Reduced fuel burn and operating costs

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Aircraft Engine Gas Path Deterioration and Fault Examples

Turbomachinery Deterioration

- **Fouling**
- **Corrosion**
- **Erosion**

Turbomachinery Faults

- **Foreign object damage**
- **Blade/Vane failure**

Controls and Accessories Faults

- **Sensor faults**
- **Actuator faults**
- **Wiring harness faults**
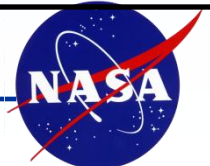
Aircraft Engine Maintenance Actions

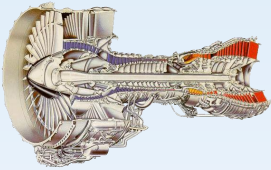**On-Wing Maintenance**

Engine Water Wash

Engine Overhaul

Gas Path Diagnostics Engine Fault Isolation Approach *

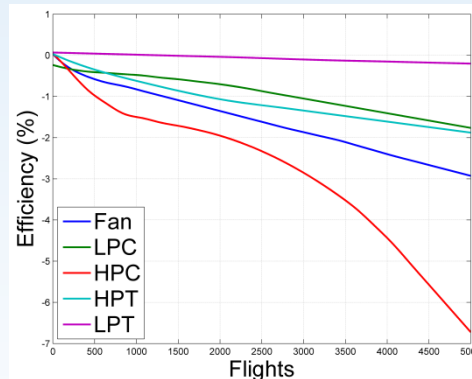**Deteriorated Turbomachinery and Gas Path Faults**

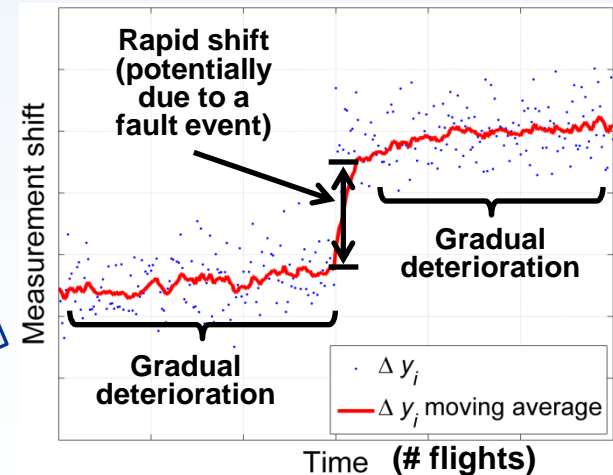**Resulting in**

Degraded module performance

Producing

Changes in measured parameters

Permitting correction of

Allowing isolation of

* Adapted From "Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines" by Louis A. Urban, 1974.
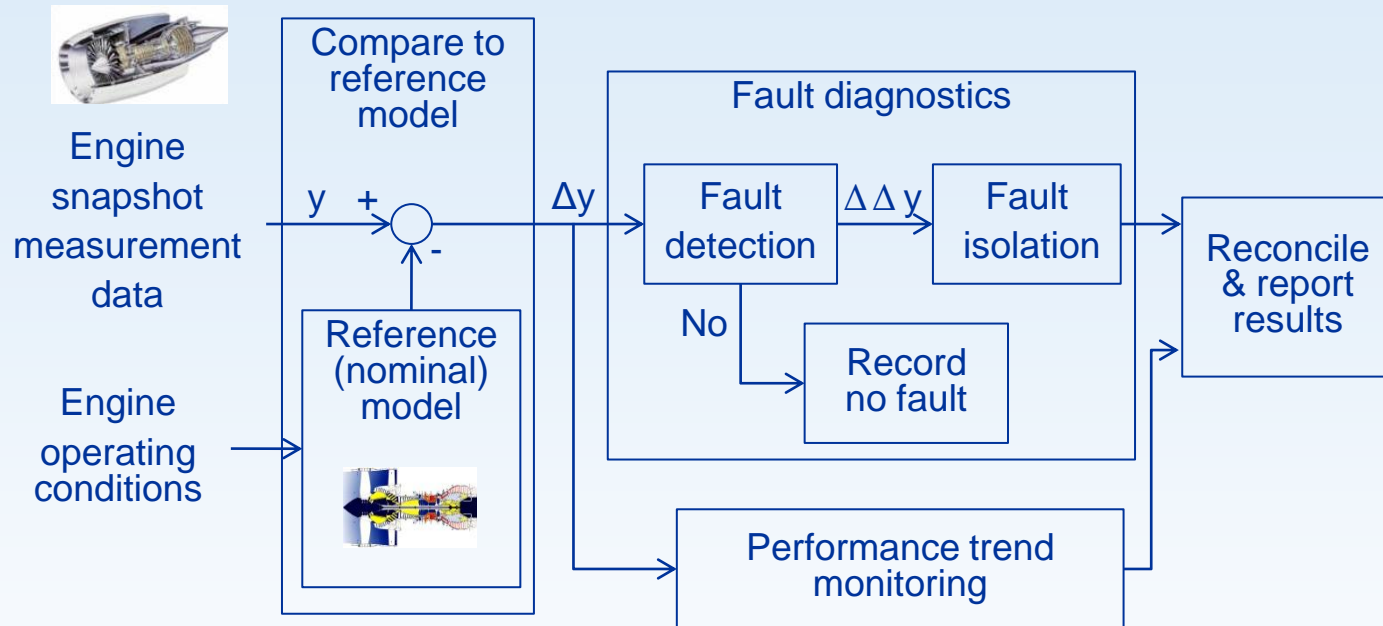

Efficiency (%) vs Flights
- Fan
- LPC
- HPC
- HPT
- LPT

Measurement shift vs Time (# flights)

Rapid shift (potentially due to a fault event)

Gradual deterioration

Gradual deterioration

Δy_i

Δy_i moving average

Ground Station Performance Trend Monitoring and Gas Path Fault Diagnostic Process*

* Reference: Volponi, A., Wood, B., (2005), "Engine Health Management for Aircraft Propulsion Systems," The Forum on Integrated System Health Engineering and Management (ISHEM) in Aerospace, November 7-10, Napa, CA.

Conventional Performance Estimation and Gas Path Fault Diagnostics (based on "snapshot" measurements)

Performance Estimation

Steady-state measurement process:

$$\Delta y = H \Delta h + v$$

Δy — sensed output vector

Δh — health parameter vector

H — influence coefficient matrix

v — measurement uncertainty (N(0,σ) with covariance R)

Performance estimation:

$$\Delta \hat{h} = \left(P_h^{-1} + H^T R^{-1} H \right)^{-1} H^T R^{-1} \cdot \Delta y$$

P_h — health parameter covariance matrix (defined *a priori*)

Gas Path Fault Diagnostics

Steady-state measurement process:

$$\Delta \Delta y = H_f \Delta f + v$$

H_f — fault influence coefficient matrix

Δf — fault vector

Diagnostics performed applying a single fault assumption:

- Assumes that rapid/abrupt performance change is most likely due to a single root cause
- Weighted least squares estimation applied to produce an estimated fault magnitude for each fault type.
- Estimated fault that best matches observed fault signature is classified as fault type.

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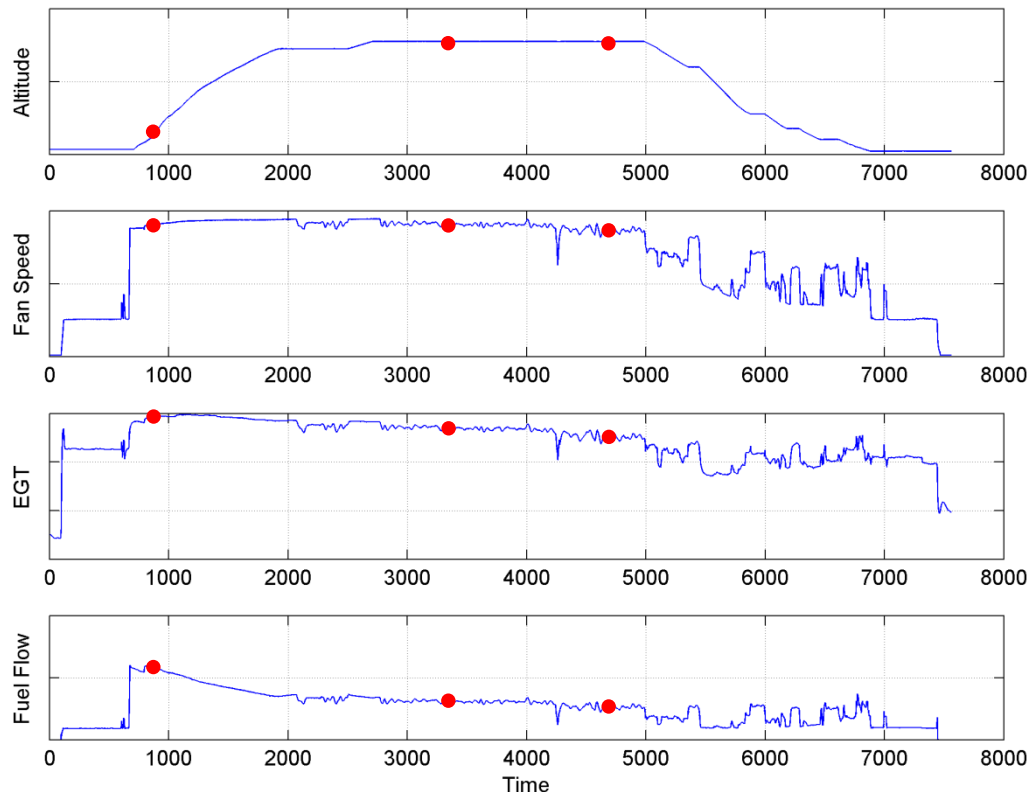
Expanding Quantity of Available Data

Example Commercial Aircraft Engine Flight Data
- Denotes conventional "snapshot" measurement point

Data Transfer

Emerging Trends

- Increasing flight data recording capabilities
- Flight Operations Quality Assurance (FOQA) programs provide operators access to full-flight data
- Dedicated processors for analyzing data on-board

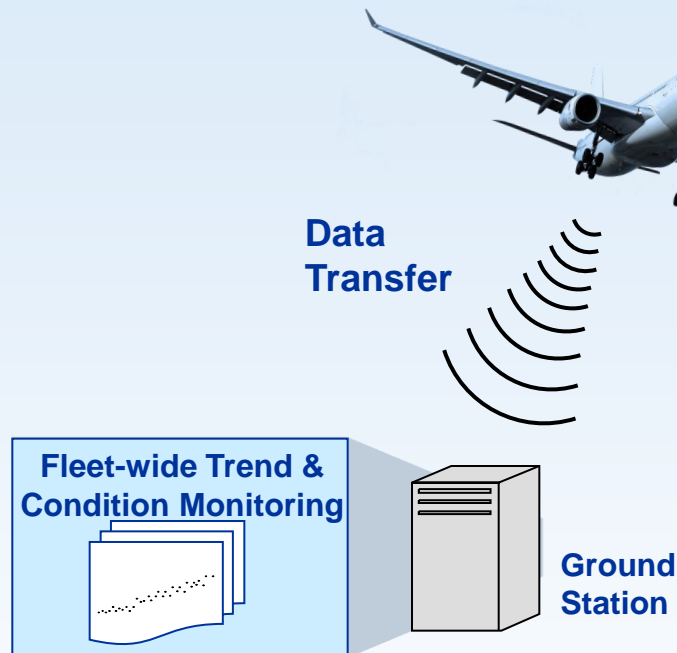*Expanded Data Quantity Provides both Challenges and Opportunities!*

Expanding Quantity of Available Data (cont.)

Data Transfer

Fleet-wide Trend & Condition Monitoring

Ground Station

Potential Benefits:

- Reduced diagnostic latency
- Improved fault detection and isolation capabilities
- Improved prognostics and remaining useful life calculations
- Applied for development of improved engine models

Challenges:

- Streaming data analysis capabilities
- Transient diagnostic techniques
- Data mining techniques for information discovery and extraction
- Efficient data compression and data management strategies
- Effective leveraging of redundant sensor measurement information

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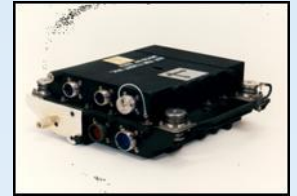
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Data Access and Data Sharing

- Access to aircraft engine data is often limited due to proprietary issues and liability concerns

- Access to faulty engine data is rare
  - Engine faults occur infrequently, and when they do occur "ground truth knowledge" of actual fault condition is not always available

- Mechanisms to sanitize and share data between "data owners" and solution providers are desired
  - NASA Ames DASHlink (Discovery in Aeronautics System Health) provides an online resource for data and algorithm development and sharing

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New Sensor Suites

- Gas path methods primarily rely upon the sensors installed for engine control purposes
    - In some cases the trend is to reduce the number of control sensors in order to reduce cost and weight and increase reliability
    - Health management benefits of sensors is often a secondary consideration

- It is difficult to justify adding additional engine sensors solely for health management purposes
    - Reduce cost/weight and increased reliability of existing sensors is desired
    - Additional sensors must have strong cost-benefit justification
    - Often dual-use functionality is necessary

- New sensors added for advanced control purposes can potentially be leveraged for health management benefits
    - Examples: tip clearance sensors, active control sensors, etc.
    - Requires new feature extraction and data synchronization techniques
    - Must relate any new information back to engine health

- Effective sensor selection tools are necessary to help end users assess the health management consequences of adding/removing sensors
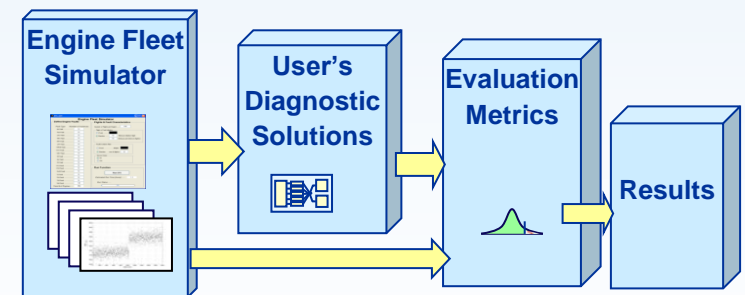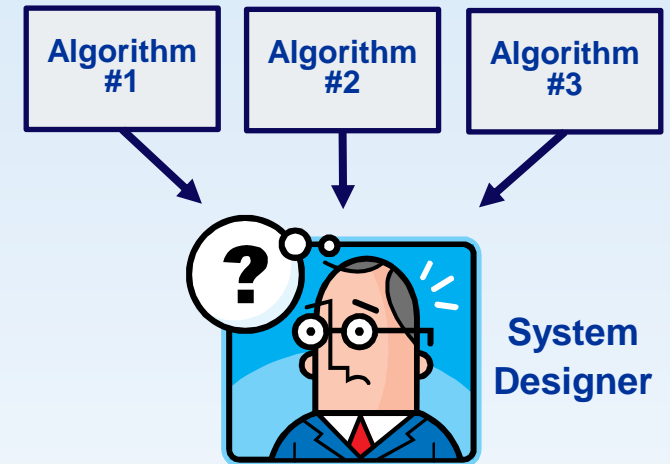
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Benchmarking and Comparison of Candidate Health Management Methods

- Engine Health Management (EHM) related R&D activities have increased significantly since the late 1990's. However, due to the use of different terminologies, applications, proprietary data, and metrics there is no basis of comparison

- Standardized metrics can enable diagnostic method performance to be reflected in a common format
  - SAE Committee E32 Aerospace Propulsion Systems Health Management publication ARP5783, "Health and Usage Monitoring Metrics: Monitoring the Monitor"

- Public benchmarking problems can facilitate the development and comparison of candidate health management methods against a common problem
  - The Prognostics and Health Management (PHM) Society Conference puts forth a data challenge problem annually
  - NASA's Propulsion Diagnostic Method Evaluation Strategy (ProDiMES) enables gas path benchmarking

System Designer
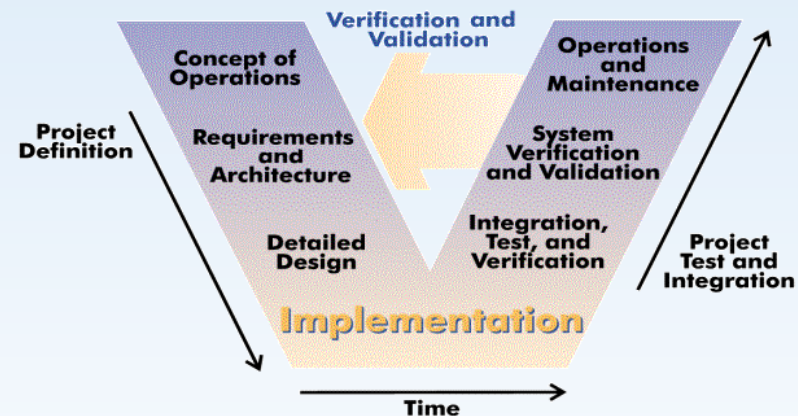

ProDiMES Architecture

Verification and Validation
Tools and Techniques

Engine health management technology is growing in its breadth of application and its complexity

Presents a need for improved verification and validation tools and techniques to reduce development time and cost

Verification and Validation Process

- Certification applicants must adhere to regulatory agency certification requirements
    - DO-178C, Software Considerations in Airborne Systems and Equipment Certification, will be the primary document by which the certification authorities will approve all commercial software-based aerospace systems
    - SAE E32 will soon publish ARP 5987, Guidelines for Engine Health Management System Software and Airborne Electronic Hardware Assurance Levels
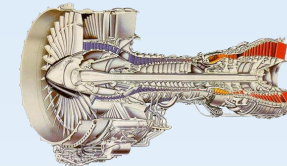
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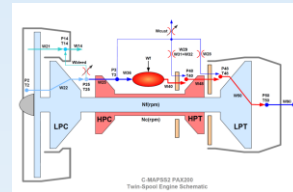Controls and Dynamics Branch

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Models for Health Management Applications

- Algorithm developers must keep in mind that engine models are imperfect
  - Engine models are 1D; actual engine is multi-dimensional
  - No two engines are the same
  - Sensors aren't modeled correctly
  - Model accuracy during transients and at off-design operating conditions is notoriously poor
  - Models developed during engine design phase aren't necessarily updated once engine goes into production; design changes aren't always modeled

Engine ≠ Engine Model

- Model-based health management algorithms must be robustly designed to account for model imperfections

- Cost effective techniques to update/maintain models over an engine type's lifetime of use are desired

- Hybrid modeling (analytical + empirical) techniques hold promise for capturing engine-model mismatch
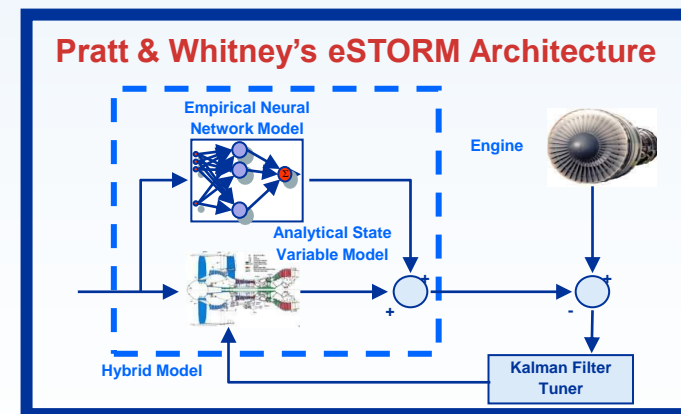

Pratt & Whitney's eSTORM Architecture

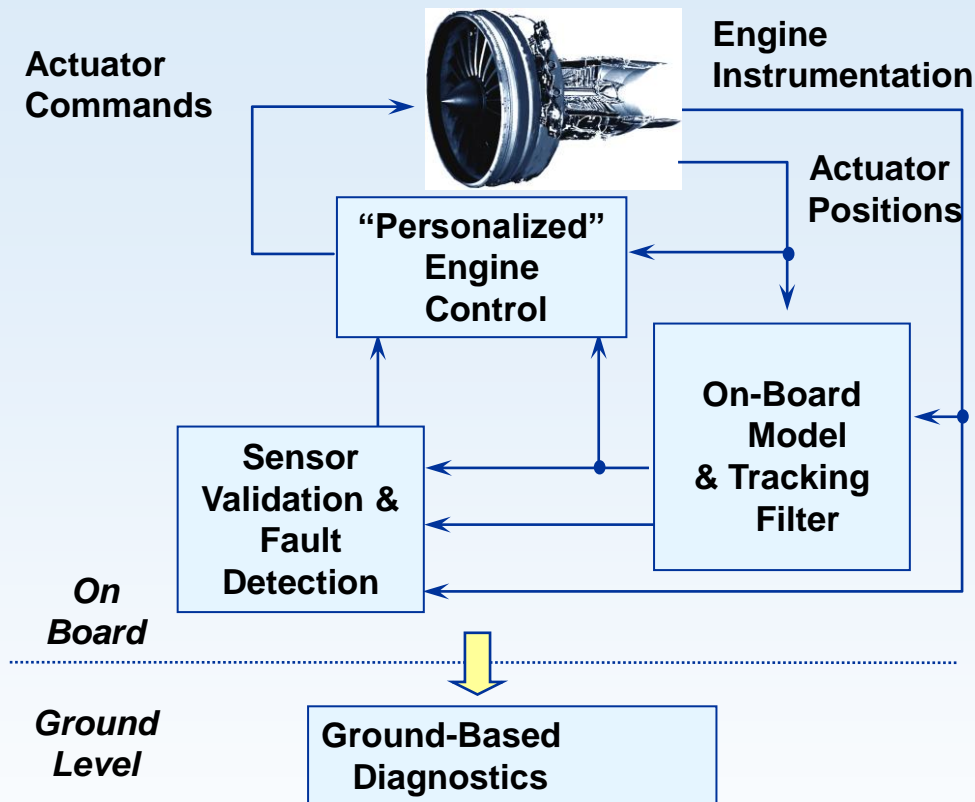# Glenn Research Center
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Model-Based Control and Diagnostics Concept

Model-Based Control and Diagnostics Architecture

Diagram labels:
- Actuator Commands
- Engine Instrumentation
- Actuator Positions
- "Personalized" Engine Control
- On-Board Model & Tracking Filter
- Sensor Validation & Fault Detection
- *On Board*
- *Ground Level*
- Ground-Based Diagnostics

Related Technology Challenges:

- Model Accuracy
  – At steady-state and transient operation
  – Sensor dynamics
  – Ability of tuning parameter adjustments to reflect engine performance deterioration effects in engine outputs
  – Hybrid modeling (e.g., eSTORM) helps address engine-model mismatch

- Verification and Validation
  – Coupling with control necessitates higher level of software assurance

- Underdetermined estimation problem (fewer sensors than unknown health parameters reflecting deterioration)
  – NASA-developed optimal tuner selection methodology provides systematic design approach for minimizing error

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Kalman Filter-Based Performance Estimation
(based on streaming measurement data)

Performance Estimation

Dynamic measurement process:

$$x_{k+1} = Ax_k + Bu_k + Lh_k + w_k$$
$$y_k = Cx_k + Du_k + Mh_k + v_k$$

k	discrete time index
y	sensed output vector
h	health parameter vector
x	state vector
u	actuator command vector
v	measurement noise ($N(0,\sigma)$ with covariance R)
w	process noise ($N(0,\sigma)$ with covariance Q)

Full-order state space equations:

$$\begin{bmatrix} x_{k+1} \\ h_{k+1} \end{bmatrix} = \begin{bmatrix} A & L \\ 0 & I \end{bmatrix} \begin{bmatrix} x_k \\ h_k \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u_k + \begin{bmatrix} w_k \\ w_{h,k} \end{bmatrix}$$

$$y_k = \begin{bmatrix} C & M \end{bmatrix} \begin{bmatrix} x_k \\ h_k \end{bmatrix} + Du_k + v_k$$

Reduced-order state space equations (replacing h with q)

$$\begin{bmatrix} x_{k+1} \\ q_{k+1} \end{bmatrix} = \begin{bmatrix} A & L^* \\ 0 & I \end{bmatrix} \begin{bmatrix} x_k \\ q_k \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u_k + \begin{bmatrix} w_k \\ w_{q,k} \end{bmatrix}$$

$$y_k = \begin{bmatrix} C & M^* \end{bmatrix} \begin{bmatrix} x_k \\ q_k \end{bmatrix} + Du_k + v_k$$

Optimal tuner selection

- *Define $q = V^*h$*
- *V^* is selected through an optimal iterative search to minimize Kalman filter mean squared estimation error in the parameters of interest**
- *Health parameter estimation:*

$$\hat{h} = V^{*\dagger}\hat{q}$$

*Reference: Simon, D.L., Garg, S., (2010), "Optimal Tuner Selection for Kalman Filter-Based Aircraft Engine Performance Estimation," Journal of Engineering for Gas Turbines and Power, Vol. 132 / 0231601-1.

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Engine Fault Test Opportunities

EHM technology development is challenging:

- Expensive to intentionally fault/fail aircraft engines
- However, dedicated testing is desired to demonstrate technology against known system "ground truth" state

Partnerships often make it possible:

- Sharing of costs, results and benefits
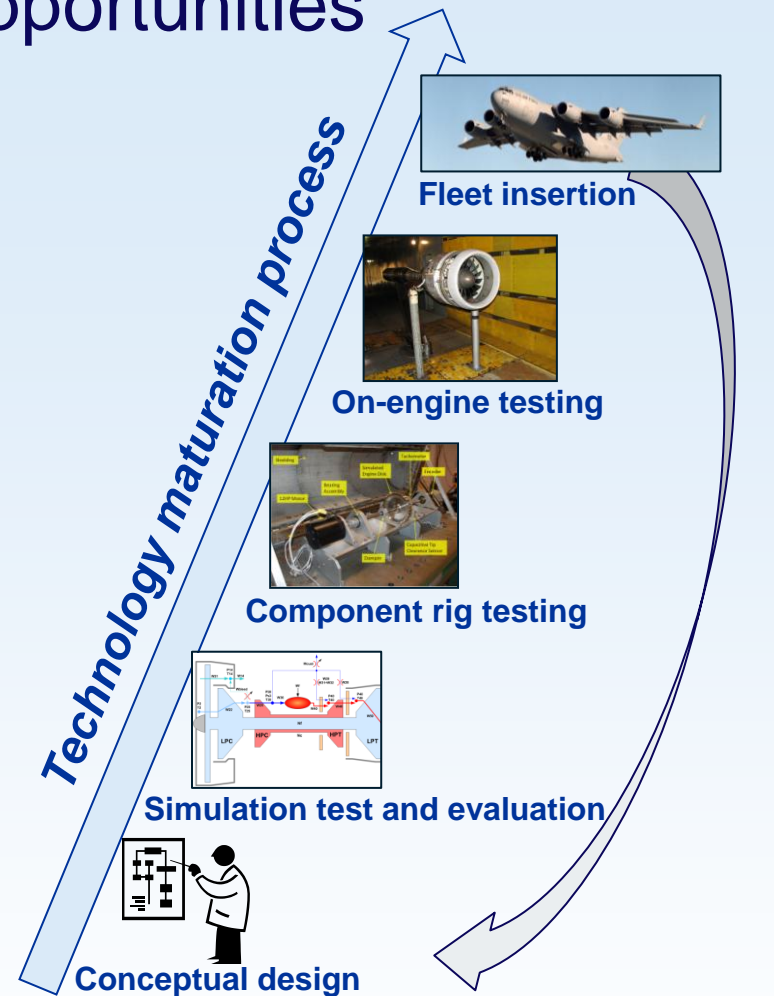- "Piggy-backing" on related tests such as mission endurance testing, acceptance testing, etc.

Examples of past engine fault testing:

- Australian DSTO fault testing on F404 Engine (1990's)
- Joint Strike Fighter (JSF) Program F100 engine seeded fault testing (1998-1999)
- FAA/Navy/NASA TF-41 engine seeded disk crack testing
- NASA Vehicle Integrated Propulsion Research (VIPR) engine testing (2011-current)

Engine Test Opportunities are Rare. When they do arise, they should be leveraged as much as possible in order to derive maximum benefits

Technology maturation process

Fleet insertion

On-engine testing

Component rig testing

Simulation test and evaluation

Conceptual design

Testing is a necessary and challenging component of Engine Health Management (EHM) technology development

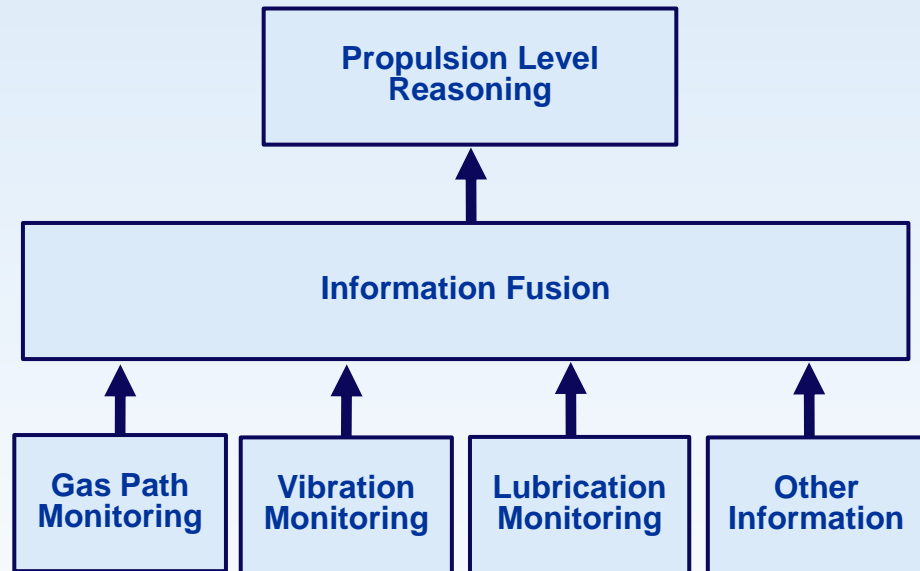# Glenn Research Center

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Information Fusion

Leverage all available information

Health inferences do not have to be based solely on gas path measurements!

- Other subsystem health information (e.g., vibration, lubrication, etc.)
- Recent maintenance actions
- Opposite engine health information
- Control information—fault codes, limit activation
- Fleet-wide engine statistics
- Domain expert knowledge / heuristics
- Negative information (the absence of information can be significant)

Information Fusion Architecture

Practical Design Considerations

Keep end user in mind

- Keep in mind that the skill of individual end users may vary considerably, and not all users will be proficient in computers or engineering terminology.
- Humans are not infallible. Consideration must be given to the fact that they may misinterpret or ignore information.
- If the user cannot operate the system, or lacks confidence in its capabilities, it may lose credibility.
- Provide quality documentation and training.

Keep maintainer of tool in mind

- Keep in mind verification and validation requirements.
- Keep expense to develop, update and maintain tool at a minimum.
- Avoid the need for substantial redesign each time the engine undergoes a hardware change or maintenance.
- Avoid the need to manually tailor the tool for each individual engine.
- Keep in mind that tool will probably be integrated into existing architecture

Try to keep the tool simple!

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Summary

Aircraft propulsion gas path health management is a key element of an overall engine health management system, providing …
- Improved safety
- Improved affordability

Challenges:
- Techniques to take advantage of expanding quantity of data including the processing, mining, and sharing of data
- New sensor suites
- The need for improved models/modeling
- Engine fault test opportunities
- Leverage all available information
- Keep the design practical

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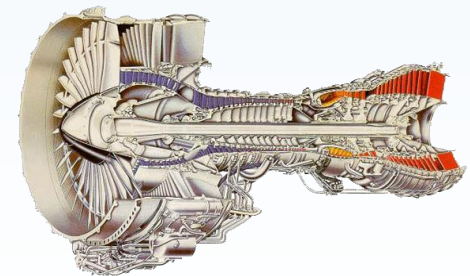
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